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Role of residential demand response in modern electricity markets

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ABSTRACT

Electricity generation must match the demand at each instant, following seasonal patterns and instantaneous fluctuations. Thus, one of the biggest drivers of costs and capacity requirements is the electricity demand that occurs during peak periods.

This paper reviews market-related problems of modern electric grids and possible solutions to address them. In particular, one techno-economical solution, namely residential demand response programs enabled by a smart grid, is analyzed and modeled in detail. The implications of this solution from both economic and policy perspectives are discussed.

The analysis results in several insights: first a local optimum does not generally lead to a global optimum, especially for complex markets; second, in this approach, there exists a disconnection between the locus of the problem (electric utilities) and the locus of the solution (change of demand); third, any techno-economic solution must be carefully designed and global impact should be evaluated to ensure that the final objective is achieved; and fourth, two-way communication is an essential requirement for the successful deployment of smart grids.

Contents

1. Introduction

Electricity is an instantaneous commodity that is expensive to store. Therefore, currently electricity generation must match the demand at each instant, responding to seasonal patterns and instantaneous fluctuations. Thus, one of the biggest drivers of costs and capacity requirement is the electricity demand that occurs during peak periods, particularly during the hours between 5 p.m. and 7 p.m. – when residents return home and prepare meals – and during excessively hot and cold days. These peak periods require utility companies to maintain operational capacity to meet such a high demand. This requisite peak capacity is often outdated, expensive, and underutilized. For example, the International Energy agency has estimated that a 5% lowering of demand would have resulted in a 50% price reduction during the peak hours of the California electricity crisis in 2000/2001 [1].

Electric utilities are extremely interested in finding a stable and sustainable solution to this sort of a problem, especially with expected widespread adoption of non-dispatchable[1] renewable power generation. Recently, smart grid technologies and demand

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[1] A term for an energy system that cannot be expected to provide a continuous output to furnish power on demand, because production cannot be correlated to load. The Energy Library: http://www.theenergylibrary.com/node/4041.

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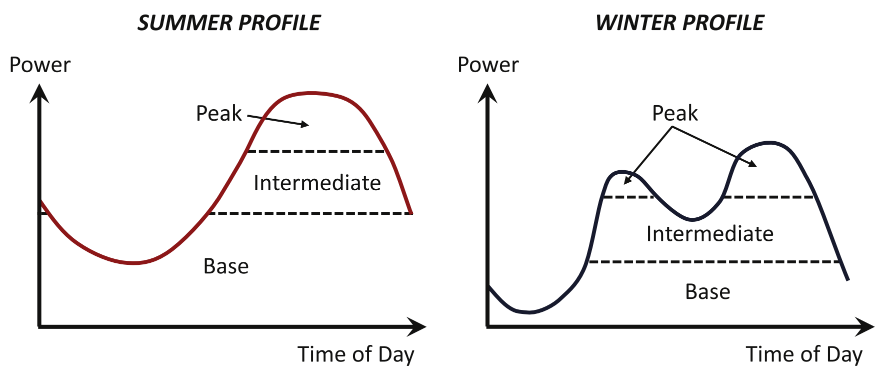

Fig. 1. Typical daily load power profile.

response programs have been proposed as a technical solution to make demand more flexible and able to adapt to power generation. Aghaei and Alizadeh present a review of challenges and opportunities for demand response programs in smart electricity grids equipped with renewable energy sources [2].

The current electrical power system is mostly mechanical, with little use of electronic sensors and control technologies. A smart grid, so-called because of the widespread use of sensors, communication technologies, computational abilities, and control systems, promises more efficient electricity generation, distribution, and consumption [3]. The smart grid requires the integration of various control and communication technologies that allow for continuous monitoring and real-time responses to demand variations and other conditions (e.g. weather changes, transmission or generation issues, etc.) [4]. For residential consumers, smart grid technologies might consist of the adoption of smart appliances and real-time demand monitoring and controlling [5]. However, currently, the rollout of smart grid technologies in the residential sector has focused on the replacement of old meters with smart meters. This allows for variable electricity pricing and the use of smart appliances.

A smart meter is an energy meter that is equipped with advanced electronics that can communicate with the energy provider and provide information about the consumer's energy use [6]. A smart appliance is one that is able to respond to external signals without direct action by the consumer [7]. In other words, the smart appliance responds to the signal sent to the smart meter automatically and independently. Smart appliances can be integrated into a network that automatically manages, monitors, and adjusts consumption in response to needs of the consumer, the availability of electricity supply, and signals from the electric utilities (i.e. the cost of energy) [8]. Optimal management of the whole system requires two-way communication between the smart appliances and the centralized controller of the electricity supplier in order to coordinate the needs of individual consumers and the needs of electric utilities. Alternatively, smart appliances can simply respond to external pricing signals, without communicating back their operating response to those signals nor communicate with each other. This requires only a one-way communication from the utility regarding the price of electricity.

Foundational to the implementation of the smart grid are demand response (DR) programs, which offer different incentives and benefits to consumers in response to their flexibility in the timing of their energy consumption in order to increase to overall efficiency of the system. These programs are needed in order to entice consumers to relinquish some control over their energy consumption. This paper focuses on the economic and policy impact of residential price-based demand response programs, focusing on time-of-use rates (TOU). A case study is simulated based on energy demand modeling [9,10] and distributed energy management [11] to simulate the effect of widespread adoption of tiered electricity pricing.

The paper is structured as follows: Section 2 introduces and analyzes the topic of the electricity market. Section 3 reviews the current literature on the topic. Section 4 presents a case study illustrating the result of the implementation of a one-way communication demand response program in the United States. Concluding remarks are offered in Section 5.

2. Definition of the problem: A distorted market

Fig. 1 reports typical summer and winter electricity demand curves for the PJM[2] region—showing base, intermediate, and peak load. Such curves might vary depending on geographical location and country, but the daily and seasonal variation in the demand remains a common issue for electric power generation around the globe.

To insure the stable operation of the electric system, and to ensure the security of supply in the face of uncertainty of available generation and variations in demand, the total generation capacity available to the system must often be significantly larger than the maximum demand, exacerbating the problem. A safety factor of 20% of excess capacity is reported in the literature [12], but in several regions of the United States this figure reached 40% in summer 2013, as reported by the U.S. Energy Information Administration [13].

In order to satisfy such a fluctuating demand, electric utilities are forced to maintain different generation assets [14]. Base-load electricity is provided by extremely reliable, inexpensive, and efficient power plants, which run continuously during the year (over 70% of the time), except in the case of repairs or scheduled maintenance. Such plants – including nuclear, hydroelectric, geothermal, and coal power plants – often take a long time to start up and are designed to work at their nominal capacity with a small degree of flexibility.

Intermediate power plants are operated between 20% and 70% of the time, with the objective of following the fluctuations of the load, curtailing their output in periods of low demand, such as during the night. These plants are typically coal- or gas-fired, including high-efficiency gas turbine combined cycles. Wind and solar power plants are typically considered intermediate power plants [14], since their operations are limited by the availability of the renewable sources exploited. Even though they are run as much as possible they do not achieve base-load availability, and they are hardly used to match peak demand, as they cannot be

[2] PJM is a regional transmission organization that coordinates the movement of wholesale electricity in all or parts of 13 states and the District of Columbia.

dispatched. Intermediate power plants fill the gap between base load and peak plants, from cost, size, and flexibility standpoints.

Peak power plants run only when there is a high demand for electricity, typically for less than 20% of the hours in a calendar year. Peak plants are generally smaller, can be started up quickly, and are flexible enough to match rapid fluctuations in the demand. The U.S. Energy Information Administration reports that in 2012 a capacity of 121 GW of natural gas combustion turbines – accounting for over 11% of the total electricity generating capacity [15] – was maintained to contribute about 3% of the overall electricity generation [16]. The average capacity factors of these plants varied significantly by time of day and region, ranging from 0% to 30%.

Peak plants are very expensive to operate and less efficient compared to intermediate and base-load power plants. The main reasons for this high cost is underutilization, as peak power plants are operated just a few hours a year, resulting in significant maintenance and capital recovery costs. Nevertheless, due to their smaller size, they are less expensive and easier to build. They are most often single cycle gas turbines that run on natural gas or, in some cases, oil derivatives.

Fig. 2 reports the load duration curve for the three categories of power plants.

The exponential increase in electricity price for peak generation is clearly shown in Fig. 3, which reports the average aggregate wholesale electricity price in the PJM market during 2011 and 2012 summer operations.

Fig. 4 reports the frequency distribution of hourly wholesale generation cost and the average retail price of the PJM Real-Time Energy Market in 2012. In the United States the electricity market price is regulated, resulting in a fixed retail electricity price, which is the price that consumers see. This is set by the regulator to maintain a profit margin for the electric utilities and at the same time protect consumers.

The disconnection between supplier cost and retail price has been observed in previous studies [19]. In Fig. 4 profit and loss areas are shown. In this example the cumulative loss is 57% of the cumulative profit (ratio of red and green areas).

As a result, utilities are constrained by the price that they are allowed to charge a customer, and consequently the revenue that can be made on any given kWh of electricity sold. The profit that the utilities make is dependent on the generation cost. As Fig. 4 shows, for approximately 92.5% of the time, the cost of electricity is below the retail price, and therefore, the utilities operate at a profit. For the remaining 7.5% of the time, utilities actually operate

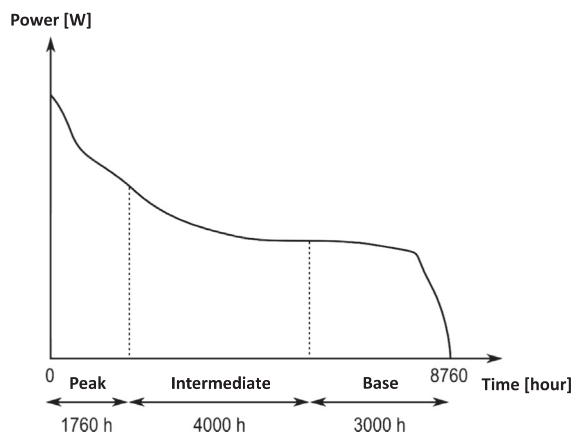

Fig. 2. Load duration curve. Adaptation from [17].

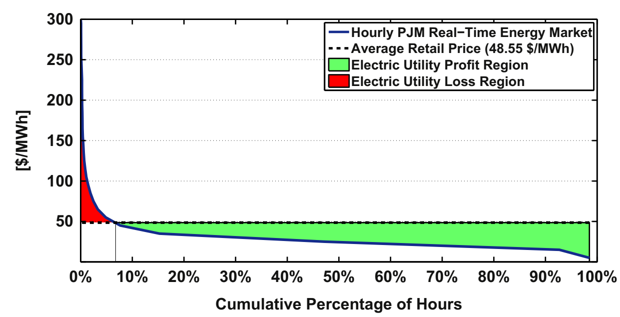

Fig. 4. Distribution of average hourly wholesale energy prices and retail price for PJM market in 2012. Data from [18]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

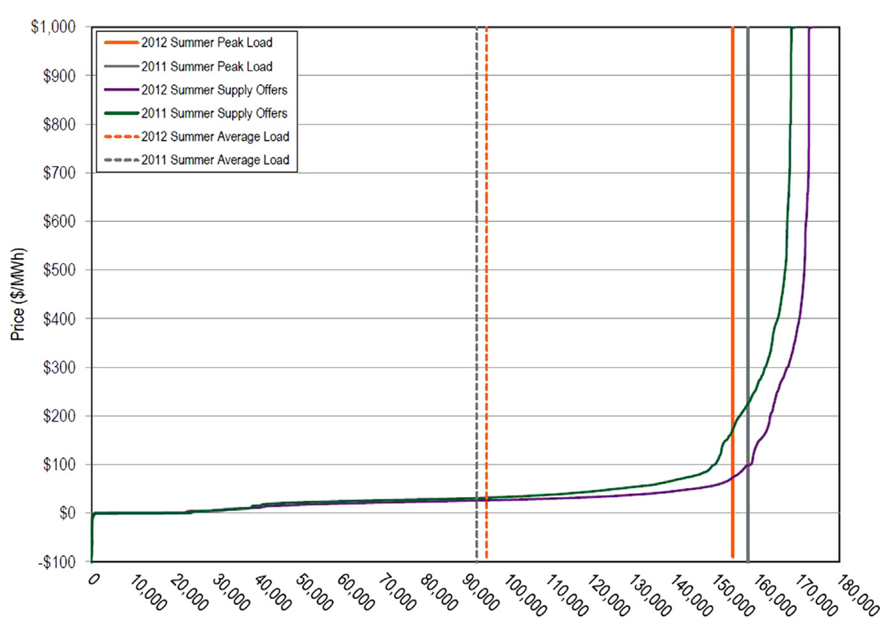

Fig. 3. Average PJM aggregate supply curves: Summer 2011–2012. From [18].

at a loss. This results in an increased average electricity retail price. Reducing the demand during this high-cost period, would reduce the average retail price, and thus would save consumers money.

One of the challenges in the operation of electric grids is that generally consumers are protected from the volatility of the wholesale market even in so-called deregulated markets. In the United States, deregulation refers to the wholesale market not to the retail market. In a competitive unregulated market, the marginal cost should equal the marginal price, but in the energy market this is not the case. Consequently, during peak periods electric utilities are forced to sell electricity at a price that is significantly lower than the marginal cost of generation. This has a twofold effect: first electric utilities are producing electricity at a loss, jeopardizing their profitability; second there is no economic incentive for demand to adjust to this higher cost and move towards the market equilibrium point. Under the current regulatory framework, during peak periods, consumers see prices that are below those that a utility would normally be willing to charge in an unregulated market. Since the utility is constrained to both supply the electricity and to charge the regulated price, demand and supply costs, averaged over time, are actually higher than what they would be in an unregulated market.

Therefore, higher generation costs during peak periods are not reflected in retail electricity prices seen by the final consumers. In essence there is an economic "iron curtain between the wholesale and retail markets" [20] meant to protect the final customers. However, this protection also creates the situation in which consumers are unaware of the cost differential of generating electricity during peak periods. Therefore, with a flat electricity price, consumers have no economic incentive to respond to changing generation costs. Demand response models are intended to take down this iron curtain by providing information (e.g., about generation costs) and allowing consumers to make decisions based on that information.

In light of this, it is in the interest of the electric utilities to find a way to smooth out demand to avoid the high costs of meeting this peak demand, resulting from the peculiarities of the electricity market where supply is forced to match demand at each instant.

There are five possible mechanisms for addressing this problem:

1. Storage of excess electricity during non-peak periods for use to match peak demand;
2. Deregulation of the electrical market;
3. Direct load control by the utilities;
4. Energy conservation and efficiency and education;
5. Techno-economic solutions.

Large scale electricity storage is currently expensive. There are several methods of storing electricity. The most commonly used method is to use the electricity to pump water to an elevated height, hold it in a reservoir, and then use gravity and the potential energy stored in the water to turn turbines when the energy is needed. However, this form of storage requires significant tracts of land and water, which are not always readily available. Alternatively, energy can be stored in electrochemical storage devices, typically batteries. However, batteries of the kind needed to support large electricity demand are still prohibitably expensive.

Deregulation of the retail electricity market is impractical for political and socio-economic reasons. Likewise, complete direct load control by electric utilities would be unacceptable by American consumers and to utilities, who are concerned about privacy and legal issues. Local efforts at energy conservation, efficiency, and education are currently being made; however, these have generally proven to be insufficient at resolving the peak demand problem. This paper focuses on the use of a proposed techno-economical solution to manage this issue in the residential sector.

One of the most prominent techno-economic solutions proposed is the Smart Grid, including decentralized control and effective communication between consumers and electric utilities. Smart Grid generally refers to a class of technology people are using to bring utility electricity delivery systems into the 21st century, using computer-based remote control and automation. These systems are made possible by two-way communication technology and computer processing.

The smart grid will lead to residential demand response,[3] allowing private customers to modify their demand profiles to fit the characteristics of flexible energy supply. This enables energy consumers to participate actively in energy markets. Demand response, is the key application that allows efficient interaction between electricity demand, supply and transportation/distribution. Demand-side management is crucial for the efficient operation of these smart assets and is the key enabling technology for integration of renewable generation, allowing sustainable operation of the energy system.

3. Review of the existing literature

A review of the substantial body of literature on demand response (DR), indicates that a further exploration of this topic is warranted. The goal of DR programs is to influence consumers to change their electricity consumption patterns, or demand, in response to the needs of the supplier [21]. Demand response models are based on the assumption that consumer demand is elastic and, thus, that consumers will respond to higher prices by reducing demand. Studies have shown that this is the case. A study at Georgia Power found that consumers reduced demand by 20% to 30% when electricity prices increased between 25 and 50 cents per kWh [22]. In another study at Gulf Power, consumers reduced their demand by 1.5 to 2.0 kW for approximately 2 hours when presented with peak prices of 30 cents per kWh [22]. Cappers and his colleagues [23] found that DR programs could reduce overall demand by approximately 10%.

Residential demand response programs can be classified into incentive-based and price-based programs [21,24]. Both are established by electric utilities to change consumption patterns by effectively changing the cost of electricity for consumers, and to increase system reliability. Consumers are not likely to be the drivers for the adoption of these technologies, as the monetary savings are not dramatic. On the other hand, significant opportunities arise for electric utilities, especially to alleviate capacity constraints and reshape the load.

Incentive-based demand response programs provide financial compensation to consumers to shift their consumption. Price-based programs provide a varying electricity price that is intended to be a signal to guide consumer consumption to better match generation. Consumers voluntarily adjust their electricity consumption based on time-based electricity prices, typically Time of Use Pricing (TOU), Real Time Pricing (RTP) or a Critical Peak Pricing (CPP) [4]. TOU rates are defined as different electricity prices for different periods of the day or of the year. For instance, consumers might see a higher price during the day than during the period between midnight and 6 a.m. RTP adjusts the electricity prices on an ongoing basis throughout the day, following the wholesale electricity generation cost, on an hourly or sub-hourly basis. CPP is basically a TOU program, with a higher price during

[3] *Demand Response* is defined by the U.S. Federal Energy Regulatory Commission as: "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized".

heavy use or peak periods. Both incentive-based and price-based mechanisms can be used at the same time. Albadi and Saadany provide a detailed overview of these mechanisms [25].

Studies of Time of Use electricity pricing go back several decades (see for instance, [26–28]). TOU pricing has been shown to effectively shift electricity demand by varying amounts. Henley and Peirson [29] found that most consumers in their UK study, shifted demand to lower cost pricing periods. Herter et al. [30] found that consumers in California were very responsive to Critical Peak Pricing during a 15-month experiment, with participants with programmable communicating thermostats using 25% less electricity during 5 hour critical events and 41% less during 2 hour critical events. Even those participants without programmable communicating thermostats reduced their consumption during these periods by an average of 13%, showing that even an awareness of critical conditions can help reduce demand.

The smart grid technologies are enablers to schedule loads at the consumer level to save energy, reduce cost, and help grid operation; however, a residential automated Energy Management System (EMS) is needed to optimally manage such an advanced integrated system [31]. Demand-side EMSs must allow consumers to compare costs/benefits with different load schedules and automatically make decisions to optimize energy use in the household. As the electric power infrastructure is evolving towards the future smart grid, demand-side management will play a key-role to help reduce peak load, increase reliability, and allow a more widespread integration of fluctuating renewable energy sources [32].

The use of smart grid technologies requires that the consumer relinquish some operational control, at least within certain parameters. For instance, the consumer can request that a dishwasher runs sometime during the night so as to complete its cycle by 7 a.m. when the consumer wants to use the dishes. The consumer is ambivalent as to when the dishwasher cycle occurs during the night, as long as the finish-time constraint is met. The EMS schedules the cycle in order to meet the constraint of the finish time and optimize the energy use, namely minimizing some sort of cost function. This type of operation is known as a Demand Response Program because it responds to the demands of the consumer.

Many consumers have expressed an interest in and support for smart meters, smart appliances, and other smart grid technologies. On the other hand, many have also expressed significant reservations about relinquishing control of the operation of their appliances to an external controller, even when they have the ability to override this external control [33,34]. Consumers have also expressed concerns about privacy issues as consumption data and patterns are transmitted to the electricity supplier [35]. Due to consumer concerns and the limited deployment of infrastructure, the deployment and implementation of smart grid technologies have been generally limited to one-way communication, where electric utilities send some sort of signal to all theirs customers, typically a sub-hourly electricity price at 10- or 15-min intervals. In such a scenario, control and operation of smart appliances remain with the consumer. Consumption can be locally shifted or reduced in response to the price signal, but the electricity provider is still obliged to meet load demand and cannot directly control or alter it.

The relinquishment of the control and convenience of starting and using the appliance at one's own discretion typically requires some sort of an incentive, since consumers are often unwilling to change their electricity consumption voluntarily [36]. Several different incentives are proposed and tested: ranging from compensating customers for reducing their electric demand in case of a grid contingency, to sending consumers signals to encourage them to reduce demand during peak hours and to short grid-initiated curtailment events with very short notification. These are typically 10 to 30 min reductions with a 10-min warning and fall under the “ancillary services”, which help the grid operator to maintain reliable operations of the electric system.

One of the most common forms of incentive is to provide a tiered pricing system, where electricity prices are lower during low-use times. The EMS would then delay the consumption of the electricity in order to minimize the overall cost of electricity for the consumer. By introducing automatic energy management, the hope is that the system would operate more efficiently. That is, that the electricity demand can be better coupled with the generation, so as to reduce the peak demand and reduce the need for higher cost capacity. To achieve this, however, consumers must be willing to surrender some of their control.

This paper explores the economic and policy implications of residential demand response, considering the impact of tiered pricing on residential demand response. There have been efforts to measure the effects of real-time pricing and other DR incentives (see for example, [37,38]), but these have only been small scale projects and have not considered the effects of wide-spread adoption of these programs or they are based on idealized scenarios.

The goal of the simulations presented in the next section is to assess the impact of distributed egoistic residential demand response. That is each single customer optimizes its energy consumption so to minimize his or her economic expenditure, while also minimizing the disruption and interference with individual decisions.

One of the goals in the deployment of demand response programs is to smooth out consumption and reduce overall “*peakness*” of the aggregate demand. However, as the results show, optimizing individual electrical consumption in this way, does not necessary lead to a global optimum. In fact, in this case, individual optimization may actually exacerbate the very problem that the smart grid solution was designed to address.

This leads to questions about the nature of the solution versus the locus of problem. In this case, the actual problem is at the system level. The utilities are confronted with a clustering of demand into peak periods. From the perspective of an individual consumer, this is not a problem, provided that the demand is met. The smart grid technologies in this case are really more geared towards addressing the system level problem. However, the only way that this can be done is by changing individual consumption patterns. Fundamentally, there is a discrepancy between where the solution is being applied (at the consumers' level) and the location of the problem, which really occurs at the utilities' level.

Tiered electrical pricing is an attempt to provide an economic incentive for the consumer to delay consumption until the price of electricity drops, after the peak consumption period has passed. From this perspective, the incentive is successful because it does indeed result in consumers delaying consumption. At the same time, however, this incentive does not solve the original problem, which was the “*peakness*” of the demand. In fact, when each single household optimizes its demand leveraging off-peak electricity prices in order to reduce its own cost, the resulting aggregate demand may be affected by an even higher rebound peak shifted toward the off-peak period. These rebound peaks have been observed in several studies and pilot projects. For example, results from the EV Project[4] show how the introduction of a time-of-use rate plan leads to a steeper and higher peak in the average demand of electric vehicles charging equipment [39]. This rebound peak originates from the synchronization of the demand that was

[4] The EV Project is the largest deployment of electric vehicle charging infrastructure in history. [online] available: http://www.theevproject.com.

originally smoother due to the stochastic request for power of independent consumers.

Ultimately the problem is that the wrong economic signal is being sent. The source of the problem is that the utilities – the suppliers – are forced to provide electricity at a set price, regardless of the demand at that point. That is, the supply curve is actually distorted by the price regulations. Rather than allowing utilities to raise the price when the demand is high, utilities are forced to meet the demand. From the consumers' perspective, there is little or no incentive to reduce demand. The tiered pricing provides the demand to delay consumption, but not to reduce it. Thus, the problem is merely pushed back, not resolved. There is a major mismatch between the individual cost of electricity and the supply costs during peak periods.

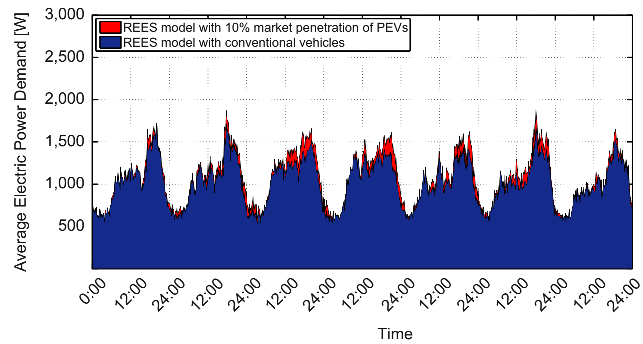

Fig. 5. Average power demand resulting from the aggregation of 100 Residential Energy Eco-Systems. First week of January 2010, Midwest region.

4. Case study: Time-of-use pricing

Recently, plug-in electric vehicles (PEVs) introduced a first connection between the energy consumptions by residential and transportation sectors, opening up new opportunities for optimization of integrated transportation-residential systems. Advanced modeling, simulation, and optimization methods are needed to understand study, develop, and operate such a complex system, which includes interactions between human, energy infrastructures, and local weather (influencing both the demand and the electricity generation). In this paper, a highly-resolved bottom-up model of integrated residential and transportation systems – including all appliances present in the household and eventual plug-in electric vehicles – is used to predict the electricity demand of a Residential Energy Eco-System (REES). REESs include all energy consumption of a household, viewing residential and personal transportation integrated into a continuum. Bottom-up models provide high-resolution data (at a defined time-step level) without relying on historical data, providing the ability to model the impact of different technologies and allowing the implementation of energy management and optimization techniques [40,41].

The personal energy consumption models have been developed by Muratori et al. based on a novel bottom-up approach that quantifies consumer energy use behaviors [9,10]. The REES model generates highly-resolved energy consumption and behavior patterns, at 10-min resolution, that are used as input for a dynamic energy management framework. The models have been validated against real measured data. A state-of-the-art dynamic energy management framework based on dynamic programming is used to find the overall optimal schedule of deferrable loads (including PEVs, when present), with the objective of minimizing the electricity-related expenditure of each residential customer. The management framework is automated, non-disruptive, in the sense that it does not require changes in people's behavior to optimally manage the energy consumption inside the eco-system and distributed (in the sense that each single household egoistically optimizes its own demand). More details on the energy management framework can be found in [42,11].

In this work dishwasher and laundry machines have been considered as deferrable loads. The algorithm schedules these appliances to complete their charging within 6 hours from the enabling time, namely the moment in which the user activates them. PEVs are also considered as deferrable loads, and are charged before the following driving event, as predicted by the REES model. This is intended to simulate the behavior of a driver, who selects a deadline for the charging when plugging-in the vehicle.

The impact of tiered electricity price structures on the aggregate residential demand is analyzed and quantitatively assessed via large-scale simulations. Results show that the introduction of time-varying retail electricity price partially achieves the objective of filling residential demand valleys, but also introduces abrupt rebound peaks in the demand.

Fig. 5 reports the average electric power profile of 100 residential eco-systems, aimed at representing the total residential electric load of a heterogeneous group of households and related PEVs (the 100 households differ in terms of size, insulation, and number and demographic profile of household members). Two scenarios are represented, namely a case where no PEVs are deployed (reference scenario representing the current situation), and a second case assuming 10% market penetration of PEVs, equally subdivided between PHEVs and EVs. Fig. 5 shows the typical attributes of aggregate residential electricity demand, characterized by significant daily fluctuations. This opens up opportunities for electric utilities to send signals aimed at reshaping the total power profile to better match the electricity generation. In particular electric utilities are interested in reducing the electric demand on power grids at critical periods (peak reduction), allow for a more constant operation of base-load power plants (valley filling), and ultimately control and regulate the total residential demand to accommodate intermittent renewable generation (load flexibility).

Recently, time-of-use (TOU) electricity rate plans have been proposed by electric utilities with the objective of re-shaping the demand profile, in particular with the intent of achieving peak-reduction and valley filling. Nevertheless, several studies and smart grid demonstration projects have shown that, when each single household optimizes its demand leveraging off-peak electricity prices in order to reduce its own economic expenditure, the resulting aggregate demand may be affected by an even higher rebound peak, shifted toward the off-peak period. Here the REES model and the proposed dynamic energy management framework are used to simulate such a scenario and quantify the effect of electricity price on aggregate residential demand response.

Widespread adoption of a two-tier time-of-use electricity pricing system has been simulated, where final price of electricity is 20 ¢/kWh between 7 a.m. and 10 p.m. (high day price), and 11 ¢/kWh between 10 p.m. and 7 a.m. (low night price). Fig. 6 reports the average aggregate demand of a group of residential households equipped with the proposed automated dynamic energy management system. The figure shows the same situation depicted in Fig. 5, after each household egoistically optimizes its own demand in order to minimize the electricity-related expenditure.

Even though the demand has been deferred towards night periods, filling the load valleys (this phenomenon would be accentuated if more loads were deferrable or distributed energy storage were present), the figure shows how every time that the electricity price drops a peak appears in the aggregate demand. Such peaks are higher and steeper than the original demand peaks that the time-of-use electricity pricing structure was intended to eliminate. This happens because all the deferrable activities wait

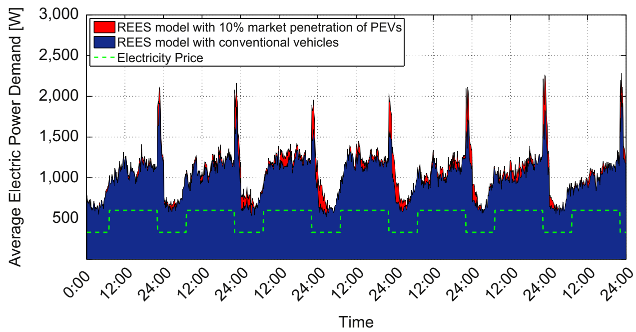

Fig. 6. Average power demand resulting from the aggregation of 100 Residential Energy Eco-Systems using automated energy management assuming two-tier TOU electricity price. First week of January 2010, Midwest region.

for the price to drop, leading to a simultaneous request of power when the electricity price changes. This approach eliminates the smoothing effect due to the natural stochastic features of residential demand, forcing demand synchronization in all the REESs.

Real-time price has also been suggested as a possible pricing structure. In this scenario when electricity price drops, consumers increase their demand. This leads to increased aggregate demand and higher generation costs, which are passed-on to consumers. With real-time pricing, consumers may actually experience higher electricity prices than if they had delayed their consumption since some of the deferrable activities cannot be interrupted once started (i.e. dishwasher cycle). This will introduce fluctuations in the system, since interruptible activities (i.e., battery recharging) will presumably be delayed in response to increased prices and then restarted once the price drops. With real-time pricing, this may happen every 10 min. Such oscillations might be very dangerous and hard to control, calling for further investigation.

5. Conclusions

This paper explores and reviews residential demand response programs, with particular focus on one-way communication smart grids where time-of-use rates are implemented as a way to reshape residential demand. Highly-resolved personal energy consumption models and a state-of-the-art distributed energy management framework are used to simulate a case-study of widespread implementation of time-of-use electricity rates. The proposed optimization framework is non-disruptive, in the sense that it does not require individuals to change their behavior. This results of the case study show that TOU programs do not effectively reduce peak demand, though they do effectively shift when this peak occurs. This is not to say that all demand response programs would be ineffective, but the complexity of the electrical system requires more sophisticated techno-economic solutions (depending for example on the specific demand and generation characteristics).

The first implication of the results is that a local optimum does not necessarily lead to a system optimum. One underlying assumption of demand response programs is that the decisions of individual consumers to change their consumption in response to price signals will lead to an overall mitigation of the peak demand. However, as these results have shown, how the incentives are designed and implemented can have a significant impact on successfully meeting this goal. In this case, having a system where the home management systems respond to pricing signals and act to minimize the electricity costs to the consumer, results in each energy management system responding simultaneously to price signals, triggering a new, steeper, rebound peak.

The second conclusion is the mismatch between the locus of the problem and the locus of the solution. The smart grid and demand response programs are designed to address what is fundamentally a problem for the electric utilities. For each individual consumer no problem is perceived, as long as electricity is available when demanded and charged at a fixed price that the consumer thinks is fair. The difficulty in finding a solution to this problem is that the location of the problem is with suppliers of electricity, not the consumers. Consumers in the United States typically see a fixed rate. Thus, there is no price connection between quantity demanded and cost of supply for consumers since consumers are generally unaware of supply cost fluctuations. Though consumers have to deal with higher electricity prices overall, the price spikes are hidden, and thus, consumers do not realize the cost problem of heavy demand periods. Since the price that utilities can charge consumers is regulated, the solution necessarily lies with getting consumers to voluntarily change their behaviour. Therefore, the utility has to provide an incentive to the consumer to change, particularly since consumers may not necessarily see a compelling reason to change.

Electrical markets are controlled on the basis of protecting consumers. However, in this case, the price controls actually distort the market by failing to provide an incentive to consumers to reduce their consumption in response to increases in supply costs. Rather than providing the supplement to the individuals that really need it, the price controls actually supplement everyone's consumption costs. This results in a lack of incentive to conserve or manage consumption more effectively in order to reduce costs. This is a classic economic and market problem. Nonetheless, a technological solution is deployed to try to alleviate this problem.

The proposed technological solution does not address the underlying economic problem of the cost to the consumer not matching the cost of production and the resulting excess demand. The distortion of the market via price regulations prevents consumers from bearing the full cost of the electricity, even when they can afford it. Thus, consumers lack an economic incentive to reduce consumption during peak periods. For policymakers, these results present a dilemma since effective policies must address the underlying problem, not merely mask it or distort it further.

Alternatively, centralized control of demand by electric utilities has been proposed, but it appears highly impractical in a country like the United States. Also, electric utilities might perceive this as a dangerous solution for their public image and are not willing for cope with privacy and legal issues related to direct load control. The only other alternatives are techno-economic solutions, including the deployment of smart grid technologies and related demand response programs. Nevertheless, these should be carefully evaluated and tested to assure that they are sustainable and effective in solving the overall problem.

The third implication is related to the design and implementation of techno-economic solutions. In this case, the solution is designed to allow consumers to automatically interact with the electrical grid and to take advantage of price incentives to reduce their overall electricity costs. However, by implementing the techno-economic solution presented in the case-study, the problem of an excessively high peak in demand is actually exacerbated. This should be a warning for advocates of technological solutions. Incorrectly designed and implemented, a technological solution may actually make the problem worse.

Lastly, the results show that the smart grid is ultimately only going to realize its potential for improved reliability, reduced peak demand, and greater efficiency if there is some form of two-way communication. This could include consumption signals from the users, or some relinquishment of control by the consumers to an external controller, this being the electric utilities or some sort of

system operator. The technology itself is neutral on whether there is a one way or a two-way communication. However, many consumers have shown a reluctance to allow external control of their appliances, even if these can be overridden by the consumer, and continue to have concerns about information sharing. Therefore, utilities and policymakers will have to ensure that consumers are educated to see the benefits of this two-way communication. In addition, demand response programs will have to provide sufficient incentives and benefits to ensure that consumers want to participate in them and do not override the technologies.

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